Naval Aerospace Medical Research Laboratory

EFFECT OF ACCELERATION FREQUENCY ON SPATIAL ORIENTATION MECHANISMS

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NAMRL Report Number 10-55

Reviewed and Approved
30-09-2010

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This work was funded by work unit number 70801.

The study protocol was approved by the Naval Aerospace Medical Research Laboratory Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects.

Summary

Background. Extreme motion environments can induce loss of visual acuity, motion sickness, and spatial disorientation. Understanding how human sensory integration of acceleration stimuli affects spatial awareness will improve models of spatial disorientation and mishap analysis. While there are numerous studies describing vestibular semicircular canal responses to angular acceleration, less is known about vestibular otolith responses to linear acceleration. This gap in knowledge is important to resolve, since sea sickness and airsickness are highly dependent on the predominant frequency of a linear acceleration stimulus. Discoveries concerning how variations in otolith stimulation contribute to motion sickness will hasten the development of targeted adaptation strategies for improved desensitization to provocative linear accelerations caused by aircraft, ground vehicle, and ship motion.

Method. With controlled laboratory off-vertical axis rotation (OVAR), gaze reflexes respond to low frequency (e.g., 0.05 Hz) stimulation as if the observer is tilted, while high frequency OVAR (e.g., 0.55 Hz) creates an illusion of translating sideways. In conjunction with this effect, low frequency OVAR is also known to cause eye torsion that attenuates the predominance of horizontal eye movements. The purpose of this experiment was to evaluate the mid range OVAR frequency (0.25 Hz) at which there is no clear predominance of tilt or translation response. The reason for evaluating this range of motion is to determine if it is the frequency at which maximum motion sickness may be observed. The finding that vestibular gaze reflexes become altered at the same frequency where OVAR becomes most sickening will have important implications for defining human tolerance in extreme motion environments.

Findings. Data were successfully collected from 10 subjects, each of whom completed three separate trials at sequences of low, medium, and high OVAR spin rates. The results of these tests revealed no significant change in horizontal and torsional eye movements between the low OVAR spin frequency of 0.03 Hz and the predicted crossover point of 0.25 Hz; however, there did appear to be a trend toward reduction of horizontal eye movement when the high OVAR rate of 0.55 Hz was compared with the low (0.03 Hz) and medium (0.25 Hz) rates. Based upon the collected data, a revised crossover rate of 0.42 Hz was extrapolated as the most probable spin frequency for inducing gaze reflex changes with the potential for triggering motion sickness.

Discussion. Determining specific spin frequencies that have a high probability of inducing motion sickness may have a significant impact on the success of military missions and safety. The results of this study have identified a potential range of circular motion with potential implications for designing future flight simulators used for training or assessment of cockpit designs. Presently, the Navy is funding a $20M construction for an advanced motion based flight simulator that is to be used as a Disorientation Research Device (DRD). To enhance the design of this device, the results of this study will be considered for inclusion with the DRD design review process as a means of ensuring that future spatial awareness research will have the opportunity to capitalize on information generated from this project.

Introduction

Understanding human visual performance, orientation perception, and motion sickness during unusual body accelerations is important to basic research in support of military operations. Body accelerations are registered by the vestibular organs of the inner ear, which contain the biological equivalent of angular accelerometers (the semicircular canals) and linear accelerometers (the otolith organs). While there are numerous studies on canal responses to angular acceleration, less is known about otolith responses to linear acceleration (Angelaki, 1996). This gap in knowledge is important, because sea sickness and airsickness are highly dependent on the predominant frequency of the linear acceleration stimulus (O'Hanlon, 1974), which is the focus of this research. Several methods have been used to test nystagmus and perception of motion in response to vestibular otolith stimulation through the alteration of orientation relative to gravity. Responses have been measured through various procedures, including active/passive pitch or roll motion and linear acceleration on a sled. Unfortunately, these methods have not always produced the most objective measurements (Clement, 1995). Using off-vertical axis rotation (OVAR) to elicit otolith response has several advantages over the methods mentioned above. With OVAR, the stimulus is administered reliably and can be reproduced with relative ease. Also, animal studies imply that OVAR allows controlled isolated stimulation of the otolith organs, since vestibularly-mediated eye movement responses can be detected during OVAR; after blocking the semicircular canals, but not after blocking the otolith organs (Wood, 2002). Unfortunately, in comparison to canal-ocular reflexes, the body of research concerning otolith-ocular reflexes is small. This may be due in part, to the difficulties associated with the assessment of spatiotemporal dependency of otolith effects on the vestibulo-ocular reflex (Angelaki, 1996).

The otolith organs of the vestibular labyrinth respond to linear accelerations caused by head accelerations with a linear component. The otoliths also respond to head tilt in reference to the linear gravitational acceleration vector (see Fig. 1). After prolonged rotation at constant velocity in a tilted axis, the angular acceleration response from the semicircular canals dissipates, while a sinusoidal change in the otolith signal (due to the gravity vector) remains. The predictable decay in semicircular canal activity permits OVAR studies to isolate otolith processing of a linear acceleration vector during rhythmical directional changes that are relevant to the subject's body.

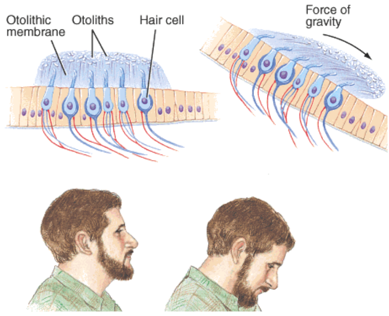

Figure 1: Response of Otolith Organs to forward head tilt.

For this reason, OVAR has been used as a laboratory analogue for linear acceleration stimulus at sea (Woodard, 1993), and has also proven to be useful as a precisely controllable nauseogenic stimulus that requires relatively minimal space.

A review of the literature on this topic provides several published hypotheses that predict the ideal OVAR spin rate for producing motion sickness at 0.3 Hz (Denise, 1996). This speculated rate of OVAR stimulus is thought to coincide with the point at which the central nervous system will have difficulty interpreting between rotational and horizontal movement; as a consequence, there will be vestibular conflict with regard to generating torsional (Fig. 2) or horizontal (Fig. 3) eye reflexes; at this critical crossover point it has been suggested the brain will have difficulty distinguishing between tilt or translational responses and the resulting sensory conflict will increase motion sickness susceptibility (Wood, 2002).

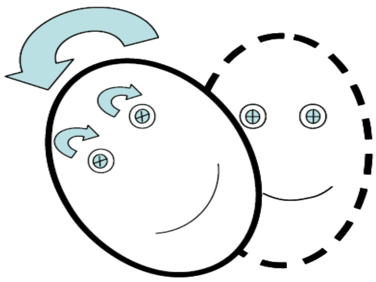

Figure 2: Eye torsion direction during head tilt

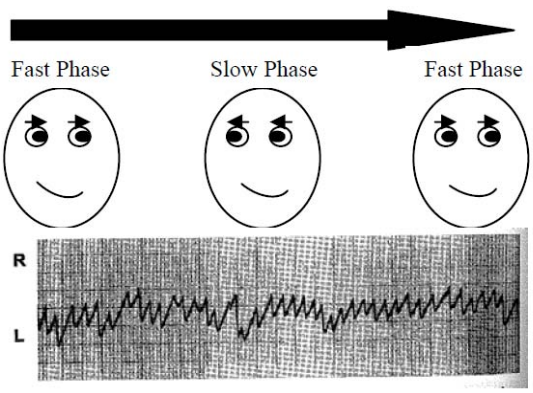

Figure 3: Horizontal nystagmus during left translation

The horizontal nystagmus depicted in Figure 3 refers to eye recordings with a characteristic saw-toothed pattern, wherein, the steeper-sloped “fast phase” of nystagmus can be considered as “looking ahead” in the direction of body motion and the more shallow-sloped “slow phase” is indicative of visually tracking a stationary scene in a direction opposite to induced head motion. During normal head translation and tilting,

these vestibularly-mediated gaze reflexes function to reduce self-induced motions when visual scenery moves across the retina of an observer that is also in motion. However, during unusual accelerations (such as may occur in flight), gaze reflexes may no longer be capable of stabilizing critical visual cues such as attitude displays and “dynamic visual acuity” for viewing outside visual references may also become degraded (Guedry, 1967).

During unusual but controlled laboratory OVAR stimulus, gaze reflexes respond to low frequency (e.g., 0.05 Hz) stimulation as if the observer is tilted (Fig. 4) while high frequency OVAR (e.g., 0.55 Hz) is processed as if the observer is translating (perceived side to side movement / Fig. 5), even though no translation is actually taking place. Figure 6 illustrates how shifting from low frequency to high frequency OVAR begins with eye torsion that gives way to a predominance of horizontal eye movements.

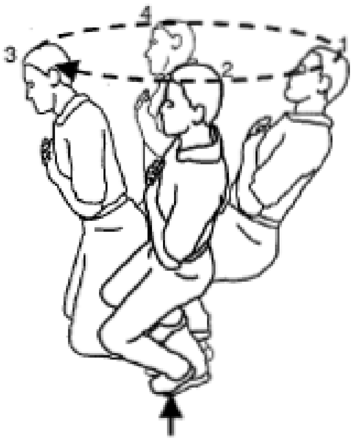

Figure 4: Perception of tilt during low frequency OVAR.

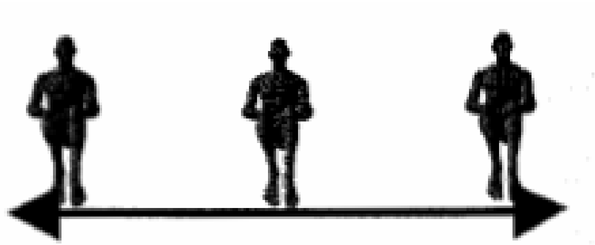

Figure 5: Perception of translation during high frequency OVAR.

Of interest for this study was the middle frequency (~ 0.3 Hz) at which there is reported to be no clear predominance of tilt or translation response; this observation has consequently led to speculation that this frequency coincides with the greatest incidence of motion sickness (Denise, 1996). This theoretical zone of maximal motion sickness is illustrated in Figure 6 by a shaded vertical band that represents the proposed “crossover point” from torsional to translational eye movement.

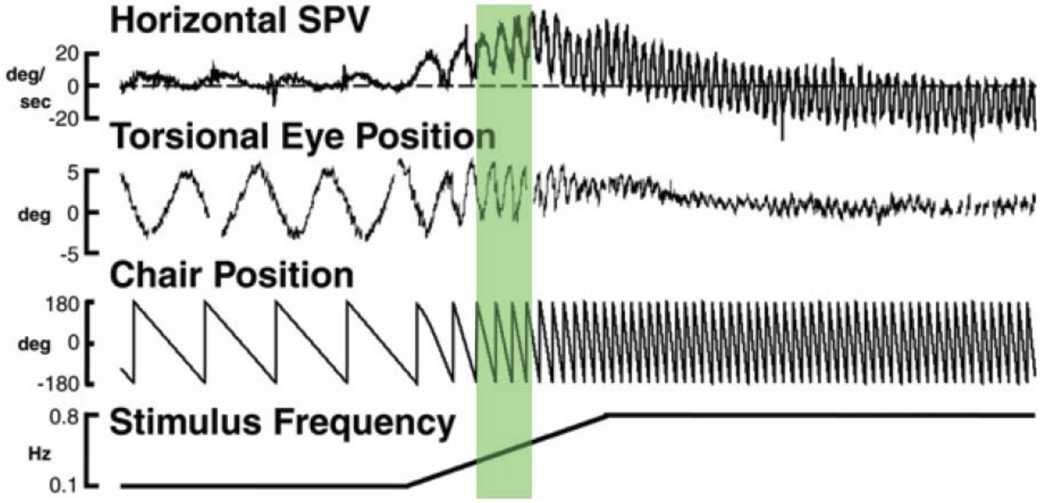

Figure 6: Green bar indicates area of shift from horizontal to torsional nystagmus as off-vertical axis rotation increases frequency (spin rate).

Determining whether vestibular gaze reflexes alter character at the same frequency where OVAR becomes most sickening may have important implications for the state of knowledge concerning the relationship between spatial disorientation and motion sickness. Previous research studies have suggested OVAR can trigger sickness or disorientation if the central nervous system is not able to resolve between tilt and translational gravity vectors; however, the findings put forth in these studies have three important limitations:

1) Motion sickness and eye movement data were obtained in separate experiments.

2) Frequencies in the 0.3 Hz range were tested directly during the motion sickness study (Denise, 1996), but extrapolated indirectly from observations made at 0.2 Hz and 0.8 Hz in the eye movement study conducted by Wood (Wood, 2002).

3) The hypothesis that 0.3 Hz is the critical crossover point for eye gaze responses, has not been directly confirmed by quantifying tilt and translation perceptions (Guedry, 1993). However, based on reports of motion perception described for studies with comparable stimulus, a low frequency of 0.05 Hz OVAR was reported as giving true sensations of tilt and rotation (Fig. 4), a medium frequency of 0.25 Hz was predicted as eliciting a mixed tilt-translation perception, and a high frequency of 0.55 Hz was found to cause sensations of linear translation without tilt (Fig. 5) (Lackner, 1978; Miller, 1970).

A primary goal of this study was to address the three aforementioned gaps in knowledge and to determine whether tilt perceptions, like eye movement responses, tend to transition to translation perceptions at higher frequencies of OVAR. Based upon the cited literature, Figures 7A, 7B, and 7C summarize the predicted relationships among vestibular gaze reflexes (Wood, 2002; Lackner, 1978; Denise, 1996). These figures suggest that at higher frequencies the tilt response decreases as indicated by decreased ocular torsion. Conversely, translation response increases at greater frequencies as indicated by the higher horizontal slow phase velocity (SPV) of the observed nystagmus. When the OVAR frequency was increased from slow to fast, some subjects reported more translation and less tilt (Fig. 7B), which suggests there is a point at which perceptual and reflexive responses transition. It is possible that this is also the point at which sensory conflict and motion sickness are most likely to occur. Based on these findings, researchers have postulated that people can be made sick in the least amount of time at the frequency represented by the line crossings of Figures 7A & 7B (i.e.; the frequency at which it is most difficult for the vestibular system to resolve between tilt and translation stimuli).

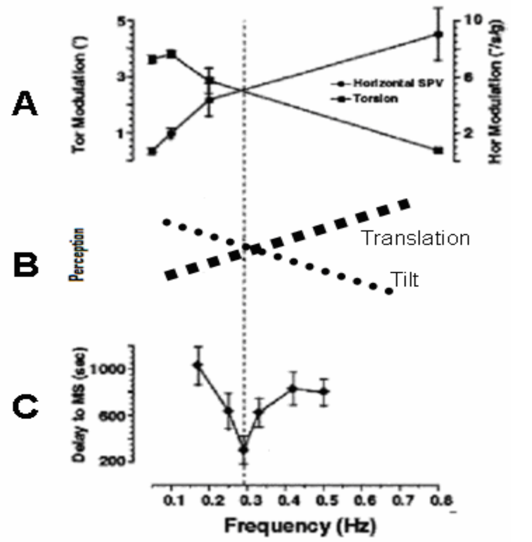

Figure 7: Predicted effects of OVAR on gaze reflexes (A), orientation (B), and motion discomfort

Hypotheses: Following several modifications generated by completion of an initial pilot study, the original hypothesis was modified and redefined for the purpose of examining how gaze stabilization responses become altered at low, medium, and high spin rates with 30 degree offset OVAR. The revised hypothesis proposed that eye torsion would occur at an OVAR frequency of 0.05 Hz, transition to horizontal eye movement would begin at 0.25 Hz, and horizontal eye movement would dominate at a frequency of 0.55 Hz.

Method

Overview of Experimental Plan: The design for this study contained a single independent variable that was created by manipulating the spin rate of a subject seated in a chair with an offset vertical axis of 30 degrees (Fig. 8). In addition to this single independent measure, the following two dependant variables were measured and compared:

1) Horizontal eye nystagmus in the head referenced horizontal direction.
2) Torsional eye nystagmus measured by differences in offset from a head referenced vertical axis.

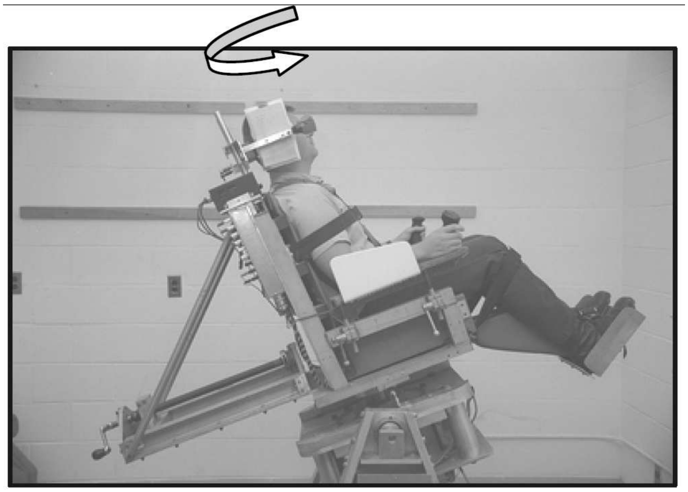

Figure 8: Off-Vertical Axis Rotation (OVAR)

Subjects. For this study, 10 subjects were used for the experimental phase of data collection. The subject pool consisted of Naval Aviator candidates recruited from the Naval Aviation Schools Command at NAS Pensacola. Subject candidates that reported a history of vestibular, oculomotor, cervical, or cranial problems (including loss of consciousness due to blows to the head) were excluded during the screening process. Participants reporting no history of motion sickness, on the Motion Sickness Susceptibility Questionnaire (Golding, 2006), were also excluded from the study.

The study protocol was approved by the Naval Aerospace Medical Research Laboratory (NAMRL) Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects. All participants were informed of their rights as research subjects and given the opportunity to ask questions. A written informed consent was obtained and a copy was provided to each participant. Participation was strictly voluntary with no compensation provided to the subjects.

Apparatus: As a means of controlling subject spin rate with variable vertical angle off-set, an off-vertical axis rotation device (OVAR) manufactured by Neuro Kinetics®, Inc., was used for this experiment (Fig. 8). The OVAR is designed to operate at constant angular velocities at different tilt angles relative to the Earth's vertical axis. The tilt angle

is manually adjustable over a 0-30 degree range. The maximum allowable chair velocity is 50 rpm for tilts between 0 and 15 degrees, and 30 rpm for tilts beyond 15 degrees. A counter-weight mechanism located behind the chair was added to give a limited amount of static balancing, thereby allowing for individual variations in subject mass/inertia distribution. The objective of the static balancing assembly was to minimize variations in chair velocity which occur cyclically according to the position of the chair rotation axis relative to the gravitational vertical.

The OVAR is also equipped with a cylindrical enclosure that contains a ventilation system to provide air circulation while maintaining subjects in complete darkness. As an added safety measure, infrared video surveillance cameras were used for visual monitoring of subjects during rotation and two-way audio communication was available via an intercom system.

For this study**,** subjects were seated in a curved car racing seat with a 5-point restraint system; they also wore safety restraints on their lower legs and ankles (to limit leg/feet motion during higher rpm) and their ribs were supported from sideways shifting by an adjustable padded torso restraint at mid-torso. Additional support was provided by standard pads or by Vac-Pacs® (Olympic Medical, Seattle, WA) which helped to immobilize the body, distribute pressure uniformly, and minimize confounding variation of information from the somatosensory system. A retractable head restraint was used to fix the subject's head relative to the chair and a neck brace was used to prevent motion of the head relative to the torso. These extensive measures helped ensure that high quality eye movement recordings were obtained.

To measure changes in eye tracking with variation in spin frequency, horizontal and torsional eye movements were recorded from a clinical eye tracking video mask (Chronos®, Inc. Berlin, Germany) and the eye tracking device processed the data after testing was completed (Fig. 9). The 3D Eye Tracker employed programmable complementary metal-oxide-semiconductor (CMOS) image sensors and was interfaced directly to digital processing circuitry to permit real-time image acquisition and processing. This architecture provided image sampling rates of up to 400 frames/s measurement, direct pixel addressing for pre-processing, and automated optical inspection (AOI) acquisition as well as hard disk storage of relevant image data. The tracker permitted comprehensive measurement of eye (3 degrees of freedom) and head movement (6 degrees of freedom). Online pupil detection and tracking runs were automatically measured and the only hands on requirement for the operator was to align the head unit and adjust the camera focus.

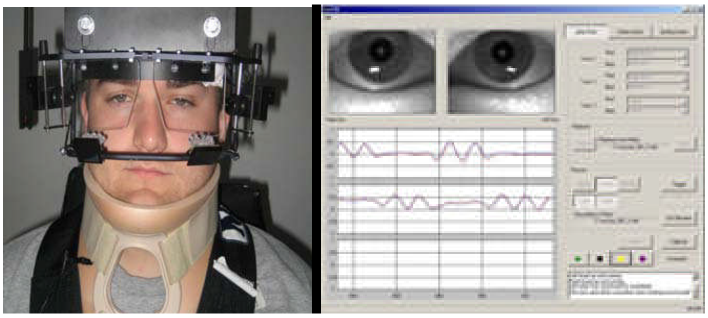

Figure 9: Chronos® eye tracking system with example of computer screen output of data for horizontal and torsional eye

Protocol. To enhance safety and comfort during OVAR rotation, subjects were restrained securely at the shins, hips, shoulders, and head. Subjects were then tilted 30 degrees and accelerated in darkness at 25°/s^2 up to one of the three predetermined terminal spin rates of 0.05, 0.25, or 0.55 degrees per second. After one minute of OVAR at constant velocity (which allowed the semicircular canal response to decay) eye movement data was collected for 12 consecutive minutes. Eye movement data was obtained during the steady spin phase (constant velocity with zero acceleration); after which subjects were slowly decelerated to a full stop and then escorted to a nearby rest and recovery area. Subjects were observed for 2 hours post-spin exposure, and then released from NAMRL. The time required for participants to complete each trial and rest period was approximately 3 hours. At least 24 hours of recovery time was provided between each of the three spin trial exposures.

Eye movements were collected and analyzed according to the method used by Wood (Wood, 2002). Horizontal eye position data collected at 100 Hz with the Chronos® system was analyzed by tracking the pupil center using a least squares fit to a clipped circular disk Model (Wood, 2002). The least squares fit method is commonly used in eye tracking to minimize the sum of squared residuals in a predictive positioning model, maximizing the fit between predicted and observed scores for more consistent eye position measurement. Torsional eye movements were derived by tracking natural landmarks in the radial pattern of the iris using a polar cross correlation function, a process that simplifies the computational task of tracking aspects of a three dimensional object (the eye) into a one-dimensional signal processing task (Haslwanter and Moore, 1995). Following differentiation and fast phase removal, non-linear least squares sinusoidal curve fits to the remaining slow components of torsional eye position and horizontal slow-phase velocity were used to determine the modulation amplitude, phase relationship with rotator position, and bias component during OVAR (Wood, 2002).

Results

The original test protocol for this research was designed to examine shifts in eye gaze reflex patterns by using OVAR at three different spin frequencies defined as 0.03 Hz, 0.3 Hz, and 0.55 Hz. After initial pilot testing revealed relatively little difference between the 0.3 Hz and 0.55 Hz OVAR ranges, the decision was made to further reduce the original mid-range (0.3 Hz) frequency to 0.25 Hz. In addition to this reduction in OVAR spin rate, the length of OVAR exposure was increased from 7 minutes to 12 minutes to improve the probability of observing changes in gaze reflex responses.

During the final phase of this experiment, data was successfully collected from 10 subjects, each of whom completed three separate trials at low, medium, and high OVAR spin rates. Figure 10 represents an example of raw eye tracking information displaying a 5 second segment of recording from one subject during exposure to low frequency OVAR.

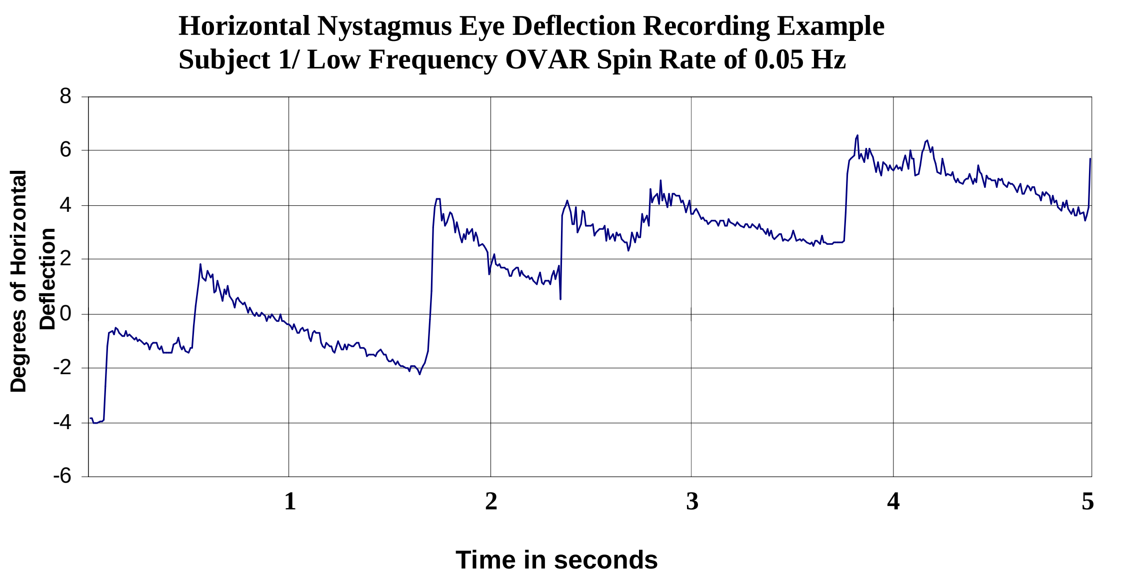

Figure 10: Example of horizontal nystagmus eye deflection 5 second recording example taken during low frequency OVAR spin rate of 0.05 Hz.

The combined data were analyzed by first sorting for potential noise artifacts and then compiling the individual information into respective digital bins for comparisons of eye gaze reflex during exposure to the three OVAR test frequencies (horizontal eye movement, Table I and torsional eye movement, Table II).

Horizontal Eye Movement Subject Mean Values

Subject	OVAR rate 0.03 Hz	OVAR rate 0.25 Hz	OVAR rate 0.55 Hz
1	-2.101673618	-0.16185856	-0.957119903
2	-1.545203674	10.82110669	-8.581271519
3	-10.44778401	-22.63029055	5.310926885
4	-27.20122986	-5.871552284	3.283742845
5	3.156842652	-5.902887548	-5.671800757
6	-8.809512184	-12.00430685	-0.305872757
7	-2.861717065	-10.24621535	-3.462994724
8	2.36459104	9.130891003	9.088958039
9	0.641423313	-20.91242378	-15.02135145
10	-20.7719382	-20.69309891	-0.141227739
Mean	-6.7 ± 8.9	-7.8 ±10.8	-1.6 ± 7.8

Table I: Subject mean values for horizontal eye tracking data collected at three different off-vertical axis rotation (OVAR) spin rates.

Torsional Eye Movement Subject Mean Values

Subject	OVAR rate 0.03 Hz	OVAR rate 0.25 Hz	OVAR rate 0.55 Hz
1	-2.869617458	0.415754707	0.459894868
2	1.098420225	2.489832387	-0.671394157
3	-0.960517155	1.788351171	-2.31786301
4	-1.128805019	-3.830164879	1.078506416
5	-0.104521209	-0.295399182	-5.571727947
6	1.964548883	-1.711021567	2.606996811
7	1.949828166	-0.664540213	1.037526095
8	-3.589213522	-0.984414848	-0.222052965
9	-2.287674617	2.636982514	-2.760698966
10	2.650608008	2.627375029	-2.229894971
Mean	-0.33 ± 2.19	0.23 ± 2.15	-0.86 ± 2.38

Table II: Subject mean values for torsional eye tracking data collected at three different off-vertical axis rotation (OVAR) spin rates.

After sorting and categorizing the data into respective OVAR frequency groups, means with variances were calculated using Microsoft Excel® statistical software (Tables I and II). Using SPSS® version 16.0 for Windows® (SPSS Inc., Chicago, IL), two repeated measures Analyses of Variance (ANOVAs) were conducted to compare torsional and horizontal eye data across the three frequency trials. Both torsional and horizontal

analyses were non-significant, F (2, 18) = .55, p = .59 and F (2, 18) = 1.25, p = .31, respectively. Though post-hoc analyses are not technically warranted with a non-significant omnibus test, frequency means were compared for each analysis using Fisher's Least Significant Difference (LSD) method in order to categorize any potential trends in the data. In combination with graphical inspection of the means for the horizontal analysis, the LSD method reveals a potential trend toward increased horizontal eye movement when the highest OVAR frequency of 0.55 Hz was compared to the 0.25 Hz OVAR spin rate (p = .16, see Fig. 11). There was no indication of any trend with regard to alterations in torsional eye movements using this method.

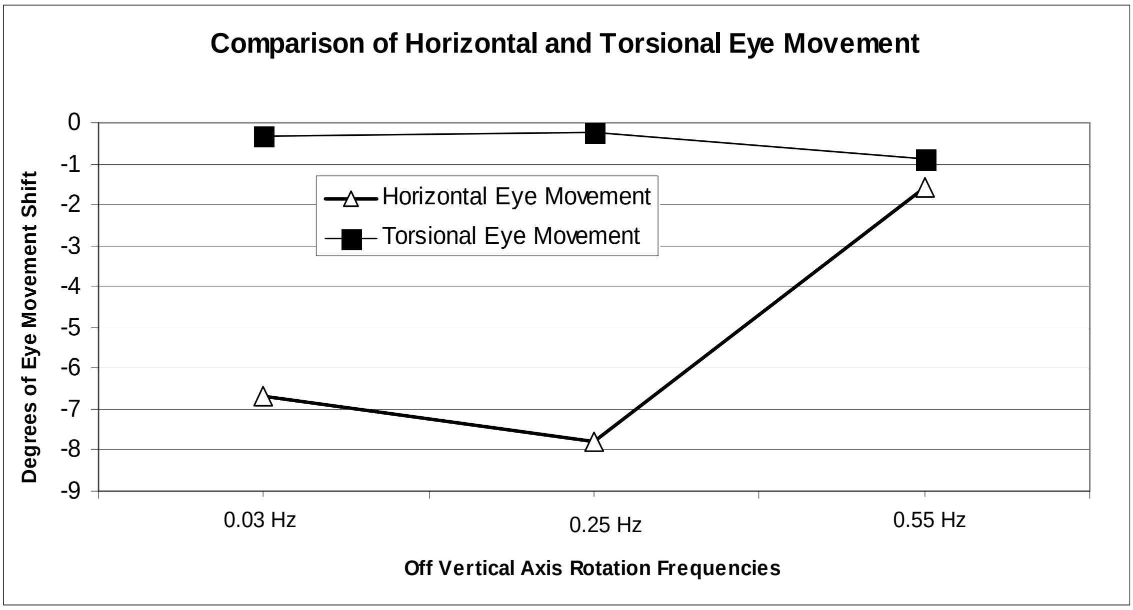

Figure 11: Comparison of subjects (N=10) mean horizontal and torsional values with changes in off vertical axis rotation (OVAR) frequency.

Discussion

The purpose of this experiment was to evaluate the estimated mid-range OVAR frequency (~ 0.25 Hz) at which it had been speculated in the literature there would be no clear predominance of tilt (torsional eye movement) or translation (horizontal eye movement). The reason for evaluating this range of motion was to investigate the prediction that spin rates near this frequency are more prone to inducing motion sickness when compared to higher or lower rates of angular acceleration. Identifying the frequency range at which vestibular gaze reflexes become altered, will have important implications for further research aimed at providing motion sickness solutions and for refining human tolerances in extreme acceleration environments.

Due to technical difficulties encountered with data recording, the original experimental design (which cited motion sickness, perception of motion direction, and gaze reflex direction as primary dependent variables) was modified to accommodate retrievable data sets that were limited to torsional and horizontal eye-tracking information. This modification necessitated changes to the data analysis approach and, although all of the originally planned measures were not tested, sufficient dependant variable data was obtained to allow evaluation of the hypothesis related to subject acceleration frequency and onset of motion sickness. These data sets were successfully analyzed for determination of shifts in eye gaze direction relative to controlled manipulations of OVAR spin velocity. The primary research goal, investigating the range of OVAR spin frequencies at which motion sickness had been predicted as most likely to occur, was achieved following analysis of the available data.

The results of these tests revealed no significant changes in either horizontal or torsional eye gaze during exposures to low, medium, and high OVAR spin rates; however, a trend was observed ($p < 0.13$) toward increased horizontal eye movement between the medium (0.25 Hz) and high (0.55 Hz) frequencies. This trend suggests the possibility that the critical crossover point for shifting from torsional to horizontal eye movement may occur at an OVAR spin rate well above the originally postulated 0.25 Hz. A review of the data calculated for comparison of variable spin rates suggest the spectrum of changes within the dependant variables (eye movement data) had a larger than expected variance that impacted the results of this study. Since the maximum observed power calculations for dependant variables of horizontal and torsional eye movement were a respective 0.29 and 0.13, the results indicate at least a three fold increase in subject number would be necessary to refine or isolate the OVAR spin rate necessary for triggering translation from a torsional to horizontal eye reflex response.

Although one of the stated goals of this research was to evaluate changes in ocular torsion during variations in off-vertical axis angular accelerations, a more advanced study on this topic should take into consideration how real world visual cues impact both the direction and amplitude of eye gaze reflexes. In order to isolate and examine vestibular driven gaze responses, the protocol for this experiment excluded visual cues; however, because the human sensory system has the ability to interact with multiple sensory channels, future efforts toward psycho/physiological modeling for reduction of motion

sickness should take into consideration the fact that visual neuro-feedback can modulate or suppress vestibular ocular torsion. Researchers investigating the relationship between visual and vestibular systems have found that during angular accelerations, ocular torsion may occur either away from, or toward the vertical gravitational axis (Gz) - depending upon the presence or absence of visual references. Based upon existing literature, there is a consensus that individuals tilting their heads from side to side while focusing on a stationary gravitationally aligned visual cue, will experience a vestibular ocular reflex (VOR) capable of counter rotating their eyes up to 10 degrees toward the Gz axis (Bucher, 1992). In contrast, if the same individuals were to view a rotating visual stimulus while their head remained stationary, they would generate reflexive eye rotation (torsion) in a direction away from the Gz axis. This visually driven ocular reflex, referred to as torsional opto-kinetic nystagmus (T-OKN), has been found to be capable of totally suppressing the VOR; while simultaneously producing up to 7 degrees of eye rotation away from the gravitational (Gz) vector (Howard, 1993).

An example of how operational environments have the potential to impact visual and vestibular interdependence can be observed from predictable in-flight head movements generated by the opto-kinetic cervical reflex (OKCR). This well documented visually driven head reflex occurs when pilots maneuver an aircraft using an outside horizon reference as a primary spatial cue (Patterson, 1997; Moore, 2008; Erickson, 2010; Fig. 12). The rationale behind this reflexive behavior is it helps pilots maintain spatial orientation by stabilizing their retinal image of the horizon during aircraft roll or pitch maneuvers. A review of the studies that have examined OKCR head movements indicate

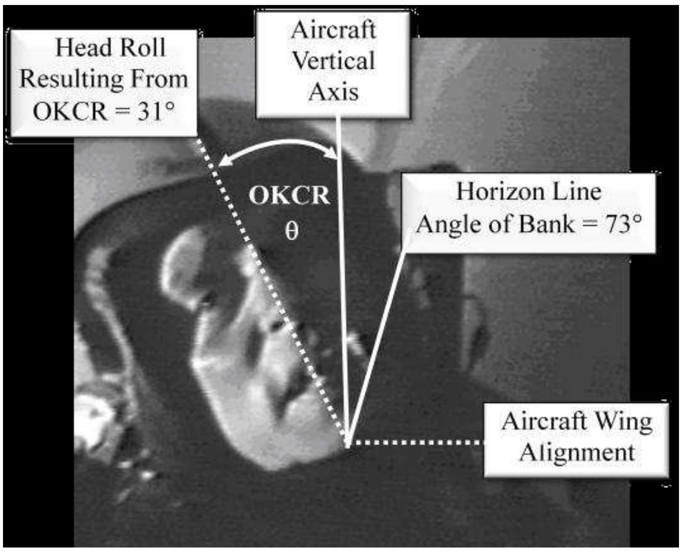

Figure 12: F/A-18 pilot exhibiting 31° OKCR (reflexive head tilt) response, during 73° banked turn. OKCR response is now a well documented quantified occurrence in real world tactical aircraft (fixed and rotary wing), fixed screen flight simulation, and in HMD virtual reality flight environments.

these off-vertical axis (reflexive) head displacements are surprisingly similar during both real and simulated flight conditions (Fig. 13). Additional research on this topic has also found that during tactical aircraft flights involving high Gz loads, OKCR occurs in the same manner as what has been documented with low Gz environments (Merryman, 1997). Since head position directly impacts both visual and vestibular alignment with real world sensory stimulus, OKCR is critical to sensory modeling because of the effect it has on the angle at which the vestibular system will sense aircraft accelerations. If accurate vestibular models are needed for proposing solutions to motion sickness, than it is imperative that vestibular motion caused by reflexive head movements become part of the modeling process.

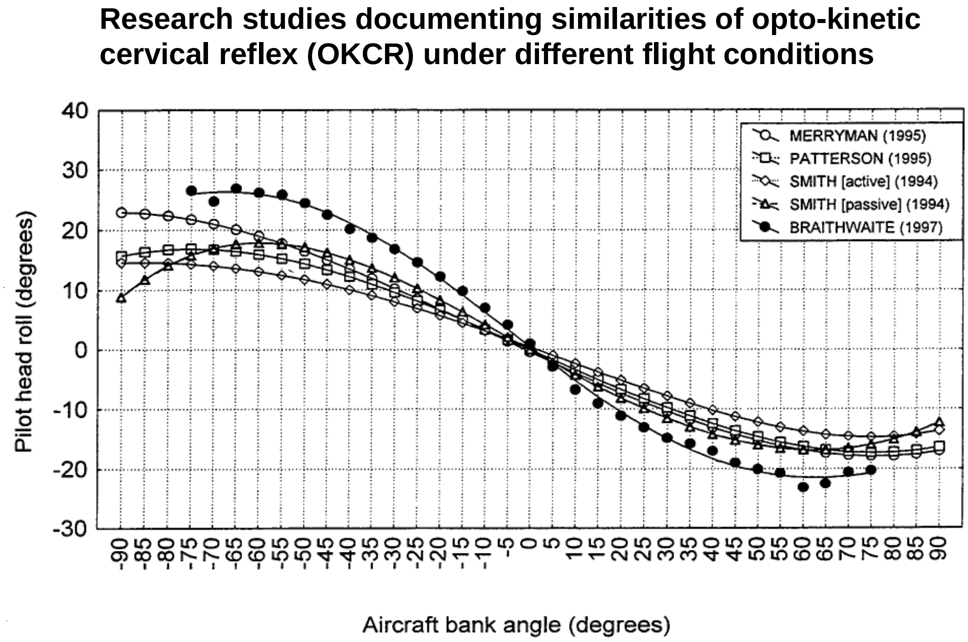

Figure 13: Comparison of head tilt responses associated with multiple OKCR research efforts.

OKCR's impact on the vestibular system is further mitigated by the presence of horizon cues; which appear to dictate the direction and magnitude of ocular torsion by establishing a hierarchy between VOR and T-OKN responses. Recent research completed by NASA scientists has confirmed previous reports of OKCR head roll response and extended these findings by documenting that both head tilt and eye rotation occur toward the horizon during simulated space shuttle landings (Moore, 2008). In addition to integrating OKCR algorithms for definitions of cockpit vestibular sensations, future efforts aimed at correctly assessing visual eye gaze responses in aviation environments, should also determine how the brain establishes reflexive priorities between the VOR and T-OKN.

Conclusion

The observations from this study appear to negate the hypotheses mentioned in the literature; which describes 0.3 Hz as being the most probable range for detrimental spin frequencies associated with motion sickness susceptibility. Based upon the outcome of this study, it could be assumed that the most sickening frequency for OVAR exposure will fall closer to the 0.55 Hz rate of angular acceleration, as opposed to the hypothesized rate of 0.25 Hz. The results from this effort may have an impact on design considerations for future military research and training devices, since it would appear from the data that the most sensory incompatible spin rates may be at a much higher rate than originally predicted. Presently, the Navy is funding a $20M construction for an advanced motion based flight simulator that is to be used as a Disorientation Research Device (DRD) for investigating fundamental and advanced concepts of spatial awareness, along with methods for preventing various types of motion sickness. To enhance the design of this device, the results of this study have been incorporated into the DRD design review process as a means of ensuring that future spatial awareness research will be able to capitalize on the information generated from this project.

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REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD MM YY)	**2. REPORT TYPE**	**3. DATES COVERED (from – to)**
30 SEPTEMBER 2010	Technical Report	OCT 2007- SEP 2010

4. TITLE
Effect of Acceleration Frequency on Spatial Orientation Mechanisms

6. AUTHORS
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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5a. Contract Number:
5b. Grant Number:
5c. Program Element Number:
5d. Project Number: NAMRL.2008.0005
5e. Task Number:
5f. Work Unit Number: 70801

8. PERFORMING ORGANIZATION REPORT NUMBER
Tech Doc No. NAMRL-10-55

8. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
Office Of Naval Research
One Liberty Center
875 N. Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(s)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Extreme motion environments can induce loss of visual acuity, motion sickness, and spatial disorientation. Understanding how human sensory integration of acceleration stimuli affects spatial awareness will improve models of spatial disorientation and mishap analysis. Vestibular gaze reflex data were successfully collected from 10 subjects, each of whom completed three separate trials at sequences of low, medium, and high off-vertical axis rotation (OVAR) spin rates. The results of these tests revealed no significant change in horizontal and torsional eye movements between the low OVAR spin frequency of 0.03 Hz and the predicted crossover point of 0.25 Hz; however, there did appear to be a trend toward reduction of horizontal eye movement when the high OVAR rate of 0.55 Hz was compared with the low (0.03 Hz) and medium (0.25 Hz) rates. Based upon the collected data, a revised crossover rate of 0.42 Hz was extrapolated as the most probable spin frequency for inducing gaze reflex changes with the potential for triggering motion sickness. The results of this study have identified a potential range of circular motion with potential implications for designing future flight simulators used for training or assessment of cockpit designs.

15. SUBJECT TERMS
spatial disorientation; motion sickness; visual acuity; vestibular otolith response; Off-Vertical Axis Rotation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**18a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Commanding Officer
UNCL	UNCL	UNCL	UNCL	20	**18b. TELEPHONE NUMBER (INCLUDING AREA CODE)** COMM/DSN: (850) 452-3486; 922-3486

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18